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FINAL REPORT

Pre-Phase A Study for an Analysis of a Reusable Space Tug

VOLUME 1

MANAGEMENT SUMMARY

Space Division

North American Rockwell

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MANAGEMENT SUMMARY

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APPROVED BY

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Reusable Space Tug

Space Division
North American Rockwell

FOREWORD

This volume presents a management summary of the results of the Pre-Phase A Study for an Analysis of a Reusable Space Tug. This study was conducted by the North American Rockwell Space Division for the National Aeronautics and Space Administration, Manned Spacecraft Center, Houston, Texas. Other volumes of this final report include:

Volume 2.	Technical Summary
Volume 3	Mission and Operations Analysis
Volume 4.	Spacecraft Concepts and Systems Design
Volume 5.	Subsystems
Volume 6.	Planning Documents

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INTRODUCTION

The introduction of the Integrated Program Plan (IPP) by NASA and the President's Space Task Group in the fall of 1969 represents a significant milestone in space planning. An analysis of this plan shows at least three normalizing characteristics of the hardware elements required to satisfy the plan:

1. Commonality – To reduce overall space costs, hardware must be made common to mission areas (earth orbit, lunar, and planetary) and user agencies (NASA and DOD) and must maximize use of common subsystems (auxiliary propulsion system, electrical power system, guidance and navigation) and components (engines and fuel cells).

2. Reusability – To further reduce costs, hardware must, once developed, have a capability of being reused many times without significant refurbishment cost or operational complexity and with no degradation of mission reliability.

3. Flexibility – To assure rapid response to new mission requirements, hardware must be flexible enough to grow or be combined with other available hardware to satisfy requirements that are not and cannot be fully defined at this time. In addition, it must be able to function effectively even if some hardware elements are removed from the space inventory.

These characteristics must be developed at a minimum cost.

An earth orbital shuttle is being designed to fulfill these objectives for a low earth orbital mission. Extension of reusable and flexible space systems beyond low earth orbit requires a space tug system. The space tug presents particularly difficult design problems because it must (1) interface with virtually every other space hardware element – earth orbital shuttle, earth and lunar space stations, lunar surface base, propellant depots, experiment modules and satellites, and the translunar shuttle; (2) operate in all mission areas – low earth orbit, geosynchronous earth orbit, lunar, and unmanned planetary; and (3) perform for all user agencies including NASA and DOD.

This nine-month study is very timely in providing an identification of the space tug mission and design requirements and the feasibility of a single modular concept for accomplishing the large spectrum of candidate missions.

The modular approach was selected to accomplish a maximum number of missions with a minimum penalty to all missions – particularly those occurring most frequently. Figure 1 shows the basic elements (crew module, cargo module, intelligence module, and propulsion module) along with ancillary kits and examples of combinations and modes to satisfy mission requirements.

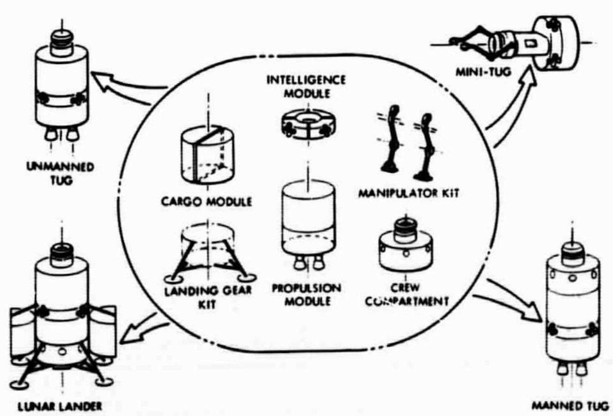


Figure 1. Space Tug Modules and Functions

This study was conducted to determine the characteristics of such a system and its ability to effectively satisfy the broad mission requirements. The study was accomplished in two phases. The first phase was concentrated on mission and system requirements. It also resulted in parametric analysis of several modes of mission accomplishment and modular system approaches. The Phase I studies resulted in the selection of three concepts for more detailed mission, operations, economic, and conceptual studies during the second phase.

This report, which summarizes the study results, is separated into the following major sections: (1) Study Objectives, (2) Method of Approach and Principal Assumptions, (3) Basic Data Generated and Significant Results, (4) Study Limitations, (5) Implications for Research, and (6) Suggested Additional Effort.

STUDY OBJECTIVES

The primary objectives of this study were (1) to determine space tug interfaces and requirements, operational modes, system requirements, hardware interfaces, and technology implications, and (2) to determine the feasibility of a single space tug design to effectively accomplish the broad spectrum of proposed and potential missions.

Other objectives were the following:

1. Determine the best subsystems and vehicle concept candidates
2. Determine the penalties in each mission arena for a single space tug design
3. Determine the capabilities and limitations of the conceptual vehicle designs in supporting the proposed missions and space tug and Integrated Program Plan objectives.
4. Achieve results of sufficient detail that a comprehensive Phase A study could be initiated immediately with the final study documentation, should NASA desire.
5. Provide management planning information, including preliminary design, fabrication, test, and operating schedule data plus key decision points, development risk information, and cost data.

RELATIONSHIP TO OTHER NASA EFFORT

The space tug is unique in that it must interface with all of the Integrated Program Plan systems. For this reason, the space tug is related to virtually all other NASA IPP study effort. These efforts include studies of the earth orbital shuttle, earth orbital space station, chemical and nuclear cislunar shuttles, orbiting lunar station, lunar surface base, SOAR, RAM, and orbital injection stage.

Other studies directly related to the space tug system or subsystems include: Chemical Orbit-to-Orbit Shuttle Study (OOS) (Aerospace Corporation); Pre-Phase A Technical Study for use of Saturn V, INT 21, and other Saturn V Derivatives to Determine an Optimum Fourth Stage (space tug) (The Boeing Company); and Astrionic System Optimization and Modular Astrionics for NASA Missions after 1974 (IBM).

Although not NASA-directed, the recent European space tug studies also are directly related. They include system studies by Hawker Siddeley Dynamics, Ltd., and the MBB group as well as a rocket engine study by Cryorocket.

METHOD OF APPROACH AND PRINCIPAL ASSUMPTIONS

The overall approach to this study is shown in Figure 2. The study end products define the feasibility of the space tug concept, recommend conceptual space tug approaches and modes for accomplishing the missions, and include planning documents that describe subsequent space tug program phases.

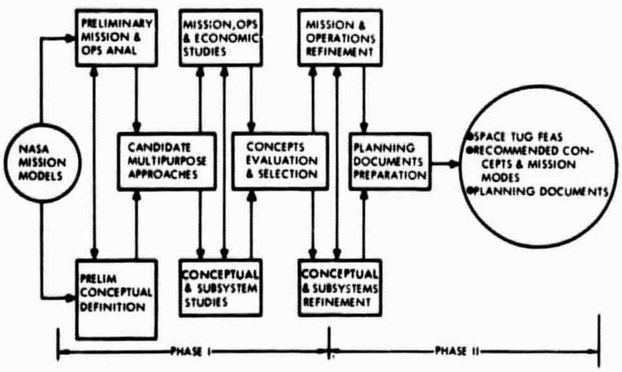


Figure 2. Study Logic

The study is separated into two phases, the first phase designating up to three concepts for a more detailed analysis during the second phase. Important initial inputs to the first phase studies were the NASA-designated mission models. Preliminary analysis of these models was conducted in both the mission and operations area and the conceptual areas to define several candidate multipurpose approaches. These approaches and the candidate mission modes were submitted to mission, operations, and conceptual analysis to obtain data for evaluation and selection of three concepts. This report summarizes results of these Phase I studies and the resulting evaluation and selection of space tug concepts. It also provides a summary of the Phase II analyses.

The Phase II studies were concentrated on mission, operations, and design refinement for the three selected space tug concepts; on certain key issues related to the comparative feasibility of the space tug and other potential approaches to mission accomplishment; and on the preparation of planning documents that describe preliminary plans for design, development, manufacturing, testing, and operations, as well as program funding and a matrix of critical space tug decision points.

The schedule for this study is presented in Figure 3. The study was initiated on June 8, 1970, and all technical work was completed at the end of January 1971. The study consisted of the four basic tasks shown in Figure 3. Primary study emphasis was placed on Task 1, Mission and Operations Analysis, on which approximately 60 percent of the total effort was spent. Three concepts were selected for refinement studies following an evaluation in October, 1970, and the results of the Phase I studies were presented at the midterm briefing on October 16, 1971.

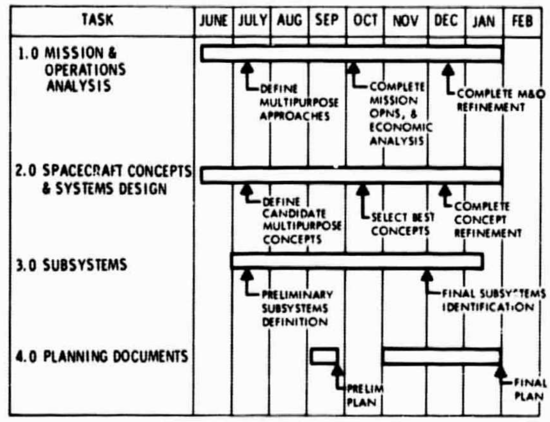


Figure 3. Study Schedule

The following summarize the most important guidelines employed during the study:

- Space-based concept
- Maximum autonomy
- NASA-provided mission model and tug IOC dates
- NASA-provided earth orbital shuttle (EOS) payload capability, payload dimensional constraints, and cost/flight
- Multipurpose, modular tug concept
- Compatibility with EOS launch constraints
- Refuelable in earth and lunar orbits

- Capable of integral use with the nuclear shuttle
- Capable of manned or unmanned flight
- Capable of quiescent status up to 180 days
- Reusable at least 10 times or a lifetime of three years
- Utilization of neuter docking devices
- LO_2/LH_2 propellants

During the study, the influence on the space tug of varying many of these guidelines was determined and, where appropriate, deviations from the guidelines were introduced into the baseline space tug concepts. Sensitivity studies conducted as variations from these guidelines included (1) ground basing, (2) varying degrees of autonomy, (3) variations in the mission model, (4) variations in EOS payload capability and cost per flight, (5) varying degrees of intelligence module modularity, (6) variations in the number of reuses, and (7) utilization of other than neuter docking devices.

BASIC DATA GENERATED AND SIGNIFICANT RESULTS

This section is separated into three parts: (1) Phase I Summary, (2) Phase II Summary, and (3) Conclusions. The Phase I summary describes the basic mission model, the space tug concepts matrix, and the rationale for the selection of three conceptual approaches. The Phase II summary describes the baseline characteristics of the three selected concepts, defines potential variations to these baseline concepts, compares the characteristics of these concepts, describes the recommended space tug evolutionary approach, and compares the space tug with other potential approaches for accomplishing the candidate missions.

PHASE I SUMMARY

Figure 4 describes in greater detail the key studies accomplished during the first phase. Selection of the several multipurpose concepts was the result of studies in both the mission and operations area and conceptual area. The NASA mission models were analyzed to determine the various mission modes that may be employed to conduct the missions; the modules and staging modes necessary for each approach were defined; and the basic mission requirements were established. Preliminary performance data were generated on a "rubber vehicle" basis to determine performance requirements for each mission mode and conceptual approach. System data for these studies were generated by conducting preliminary concepts synthesis studies which were supported by preliminary subsystems and mass properties analyses. As a result of these preliminary synthesis studies, several multipurpose approaches were selected.

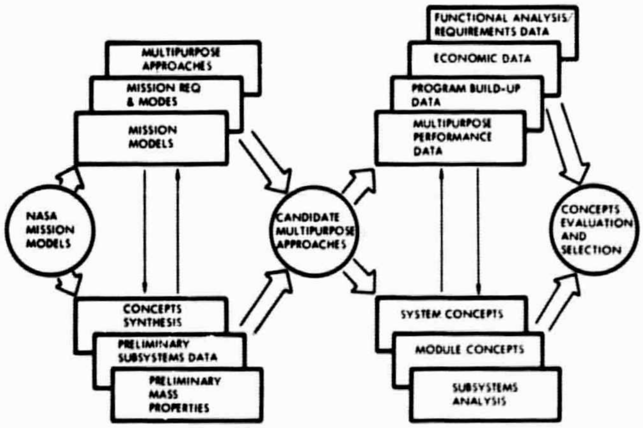


Figure 4. Phase I Studies

These approaches were subjected to both mission and operations and conceptual analysis to select up to three concepts for the second phase studies. Sufficient conceptual study was conducted to support the mission and operations studies and to determine the feasibility of the various conceptual approaches. Each of the multipurpose approaches was analyzed to develop off-loaded performance data for all of the missions. The mission models were further analyzed to develop the data necessary to establish the approach for building up the necessary space tug systems and to determine the propellant resupply cycles for the earth orbital shuttle and the cislunar shuttle. The models also describe the mission segments for each mission area. These data were the key elements for conducting an economic analysis (including analysis of a baseline mission model and variations to this model) for each multipurpose approach.

A functional analysis also was conducted for these missions to establish the space tug interfaces with other IPP systems and to define the basic requirements influencing the design of the space tug modules, constraints on their integration, and basic subsystem requirements.

The data generated was then analyzed and concepts were selected for the second phase studies.

Mission Model

The overall breadth of the mission model considered for the space tug is illustrated in Figure 5. The basic mission model includes the categories of low earth orbit missions, high earth orbit missions (e.g., geosynchronous), unmanned planetary missions, and lunar missions.

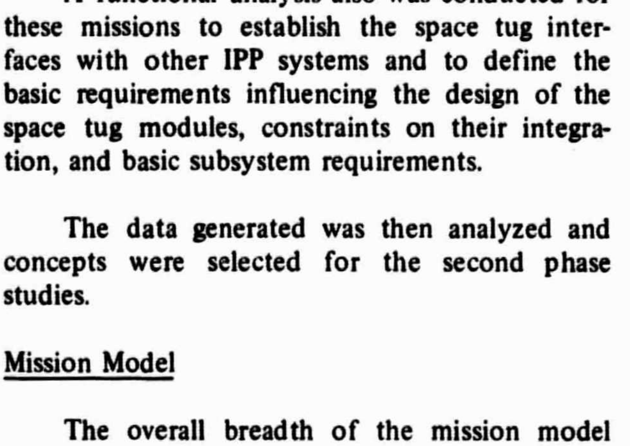


Figure 5. Spacecraft Reusability Regimes

Low Earth Orbit Missions

Although the earth orbital shuttle is capable of conducting missions in the low earth orbit regime, the space tug was considered to work in conjunction with the EOS and the space station to improve the operational efficiency for many of the missions in this area. These missions include payload and crew transfer between the EOS and space station; space station assembly and stationkeeping; and deployment, servicing, and retrieval of experiment modules near the space station.

Another category of low earth orbit missions includes the placement of payloads beyond the capability of the EOS. Typical of this category is the placement of satellites at sun synchronous conditions at altitudes up to 770 nautical miles (1430 km).

Geosynchronous Missions

The NASA mission model included placement of about 140 payloads at geosynchronous conditions during the 10-year-period from 1980 to 1990. Because of the high characteristic velocity of this mission [14,100 feet per second (4.3 km/sec)], it was considered the primary performance driver for a reusable space tug. The maximum payload weight for this mission is 10,000 pounds (4540 kg).

Unmanned Planetary Missions

The unmanned planetary missions also require high-performance capability. The inner planet missions (Mars, Venus, and Mercury) have characteristic velocity requirements of approximately 13,800 feet per second (4.2 km/sec). Payloads up to 8000 pounds (3,600 kg) have been specified. Outer planet mission characteristic velocity requirements approximate 24,300 feet per second (7.4 km/sec) with payloads up to 2000 pounds (910 kg). Because of the high characteristic velocity for outer planet missions, expenditure of the space tug is necessary in injecting the satellites.

Lunar Missions

Primary use of the space tug in lunar operations is for the delivery of payloads and crew between lunar orbit and the lunar surface. All of the space tug modules are required to conduct these operations. Before placement of a lunar surface base, early lunar missions will be conducted by the space tug from an orbiting lunar space station which may be resupplied by a cislunar shuttle. During these missions, the space tug crew module will serve as a lunar surface shelter for 4 men up to 28 days. Total payloads of up to 20,000 pounds (9100 kg) (including the shelter) would be carried to the surface and between 10,000 and 20,000 pounds (4540 and 9100 kg) would be returned to orbit.

The space tug also will be used to deliver the lunar surface base modules to the surface. Because of their large mass, the tug would be expended in accomplishing this mission. During operation of the lunar surface base, the tug will provide logistics support, transporting crew and payload between the lunar orbiting space station and the surface base.

Two or more space tugs will be used in lunar operations: one for the logistics tasks previously described and the others for space station support and for mission safety. The space tug has an inherent capability to change planes up to 90 degrees and return in lunar orbit, return to earth orbit, or descend to the surface and return with a moderate plane change, thus providing a capability for rescue and abort in lunar operations.

In addition, the space tug may provide the capability of transporting crew and moderate cargo in one direction between earth and lunar orbit by itself, or may be used to improve the efficiency of the translunar reusable nuclear or chemical shuttle as a second stage or as a stage that retrieves the translunar shuttles upon their return to an elliptical earth orbit.

Overall Mission Model Characteristics

IOC dates for the Integrated Program Plan systems used in this study are shown in Figure 6. The earth orbital shuttle will be introduced early in 1978. An unmanned version of the space tug, composed of the intelligence and propulsion modules, will be introduced about two years later to provide a capability for emplacement of payloads beyond the EOS orbital capability. During 1980 and in conjunction with space station operations, the space tug crew module would be introduced to allow manned operations for space station assembly and support. The entire tug capability will be developed by 1983 to support the lunar mission area. This will include the crew module modification to allow it to operate as a surface shelter and the development of the landing legs and cargo module.

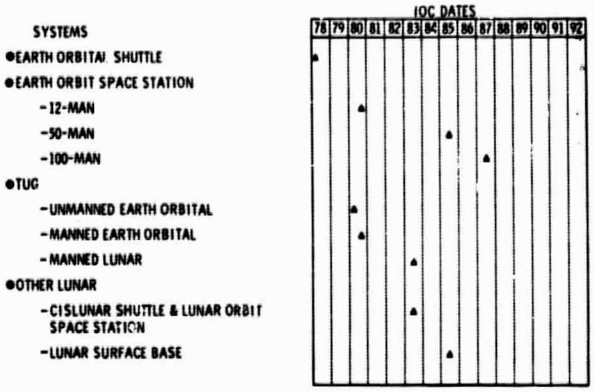


Figure 6. System IOC Dates

Figure 7 shows the number of space tug missions from 1980 to 1989 in the major categories of mission support: (1) satellite placement, which includes unmanned satellite placement in earth orbit beyond EOS capability and to the near and far planets; (2) earth orbit space station support, which includes payload and crew transfer between the space station and EOS, experiment module maintenance, and space station assembly; and (3) lunar program support, which includes propellant and payload transfer between the EOS and the cislunar shuttle in earth orbit, missions between the lunar orbit station and surface, and cislunar shuttle maneuvering in earth orbit.

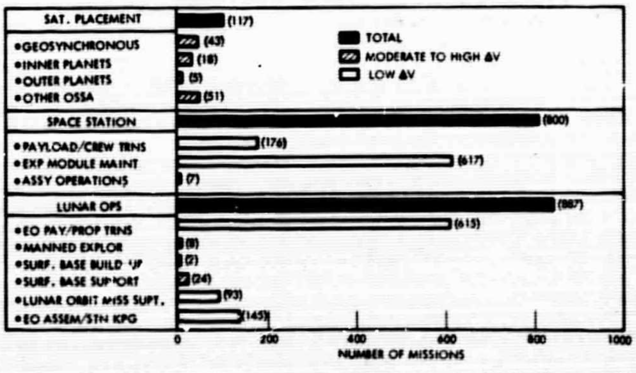


Figure 7. Space Tug Mission Frequency (1980 to 89)

As indicated, most of the missions require only a low characteristic velocity. These missions generally require the transport of relatively large propellant, cargo, or experiment modules between closely spaced low earth orbits such as between 100 and 270 nautical miles (185 and 500 km). Although the moderate to high characteristic velocity missions are comparatively low in frequency, they are significant because of the large amounts of propellant consumed. They include geosynchronous and planetary payload insertions and lunar landing missions.

The 43 geosynchronous missions assume the capability of clustering multiple payloads. This is considered to be a lower boundary of missions, which could be as high as 140 if each payload were injected separately.

While these data may imply the requirement for more than one space tug because of the split between high and low characteristic velocity missions, studies have shown that large propulsion modules, designed by the high-performance missions, have efficiencies comparable to propulsion modules optimized for the low-performance missions, provided they are off-loaded.

Multipurpose Approach Matrix

The basic approach to determine candidate multipurpose space tug approaches was to determine the driving requirements for each of the modules and to assess the method for accomplishing all of the missions utilizing various operational modes and modifications to the modules. The following sections describe the initial matrixes for the propulsion, crew, and intelligence modules.

Propulsion Module Matrix

As a result of the preliminary mission analysis, it was determined that the lunar landing and geosynchronous missións were the primary performance drivers for the propulsion module. Several staging relationships were considered for these missions, including single stages, two tandem stages, a stage with a tank set, and parallel stages. These concepts may be either totally recovered, partially expended, or totally expended in accomplishing the several missions. Both stages of two-stage systems are assumed to be of equal size (performance data indicate that equal-size, two-stage systems have performance very nearly the same as optimum two-stage systems for the high-energy geosynchronous mission). For systems with a stage and tank set, two cases were considered: (1) the tank set has the same capacity as the stage and (2) the stage and tank set are of different propellant capacities.

As a result of the initial mission and operations analyses, the concept matrix shown in Figure 8 was developed. All of the concepts originated from either the geosynchronous or lunar landing mission. Ten concepts were originally devised, but concepts 9 and 10 (not shown) were incapable of accomplishing some of the missions and required expenditure of two stages on the high-performance missions. Concept 11 composed of a 9,000-pound (4540 kg) capacity stage and a 48,000 pound (21,800 kg) capacity tank set, was developed toward the end of Phase I. This concept originates from the geosynchronous mission. The tank set is expended while emplacing a 10,000 pound (4540 kg) payload at geosynchronous conditions. The small stage and intelligence module return to low earth orbit for reuse.

CONCEPT	PROPELLANT LOADING, 1000 LB, 1000 Kg)	STAGING ARRANGEMENTS				
		GEOSYNCH	LUNAR LANDING	LOW EARTH ORBIT	PLANETARY	
					INNER	OUTER
1	80 (36)	SINGLE STAGE	SINGLE STAGE	SINGLE STAGE	SINGLE STAGE	SINGLE STAGE
2	52 (24)	TWO STAGE OR STAGE & TS	SINGLE STAGE (MODE A)	SINGLE STAGE	TWO STAGE	SINGLE STAGE
3	45 (20)	STAGE & TS	STAGE & TS	SINGLE STAGE	TWO STAGE	TWO STAGE (SECOND EXP)
4	41 (19)	TWO STAGE	SINGLE STAGE (MODE B)	SINGLE STAGE	TWO STAGE	TWO STAGE (SECOND EXP)
5	36 (16)	TWO STAGE	SINGLE STAGE (MODES C & D)	SINGLE STAGE	TWO STAGE	TWO STAGE (SECOND EXP)
6	31 (14)	TWO STAGE (SECOND REC)	STAGE & TS	SINGLE STAGE	SINGLE STAGE	TWO STAGE (SECOND EXP)
7	27 (12)	SINGLE STAGE	STAGE & TS	SINGLE STAGE	SINGLE STAGE	TWO STAGE (SECOND EXP)
8	23 (10)	TWO STAGE (SECOND EXP)	STAGE & TS (MODES B, C, & D)	SINGLE STAGE	SINGLE STAGE	—
11	9 48 (4 22)	SMALL STAGE & TS (TS EXPENDED)	SMALL STAGE & TS (MODE A)	SMALL STAGE	SMALL STAGE & TS (TS EXPENDED)	SMALL STAGE & TS (BOTH EXPENDED)

MISSION FROM WHICH CONCEPT ORIGINATED

PARTIALLY OR FULLY EXPENDED IN ACCOMPLISHING MISSION

Figure 8. Propulsion Module Matrix

The stage LO_2/LH_2 propellant loadings vary from 80,000 pounds (36,200 kg) for concept 1, which originates from the geosynchronous mission, to 23,000 pounds (10,400 kg) for a two-stage system originating from the geosynchronous mission (the second stage is expended while accomplishing this mission).

Three modes were considered for the lunar landing mission (Modes A, B, and C). Mode A required a 20,000 pound (9100 kg) round trip payload comprised of a crew module weighing about 10,000 pounds (4550 kg) and 10,000 pounds (4540 kg) of experiments, mobility devices, and expendables. Mode B required 20,000 pounds (9100 kg) to be delivered to the surface and 10,000 pounds (4540 kg) to be returned to orbit. Mode C required two surface sorties of 10,000 pounds (4540 kg) round-trip capability each for the mission. One tug carries the crew module and crew and the other carries the experiments, mobility devices, and expendables. Two-stage (tandem) operations were considered for the lunar mission but were rejected because performance was reduced in this mode. Those lunar mission concepts shown as a stage and a tank set could alternately be accomplished in a two-parallel stage mode.

Figure 8 shows the mission from which each concept originated, the staging relationship for each mission, and whether an expendable or recoverable mode is employed. As shown, the only concept that utilizes the same staging mode for all missions is concept 1, which is always a single stage configuration.

Crew Module Matrix

Figure 9 shows the types of crew modules and positions of the crew module on the propulsion module considered. A vertical cylinder was considered because of the relative ease of integrating it with cylindrical propulsion modules. The horizontal cylinder was considered because of its potentially superior functional characteristics when used as a lunar surface shelter. Diameters ranging from 12 feet (3.7 m) to 22 feet (6.7 m) were considered for the vertical cylinder.

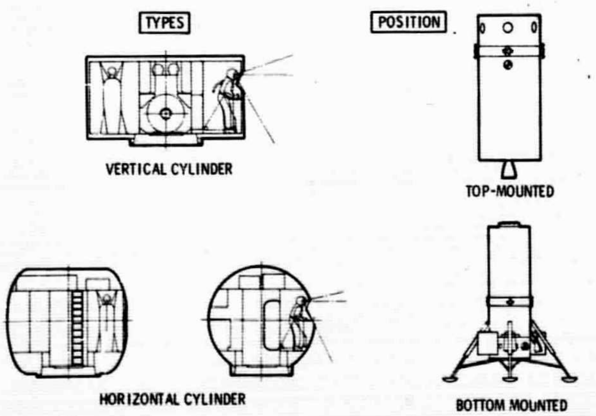


Figure 9. Crew Module Concepts Matrix

Both top and bottom mounting of the crew modules were considered to satisfy mission-peculiar functional requirements. Top mounting of the crew module is desirable for earth orbital mission functions. However, bottom mounting appeared desirable for the lunar landing missions to improve ingress and egress, to lower the center of gravity, to improve landing visibility, and to avoid excessive propulsion module loading when landing.

Intelligence Module Matrix

The three basic concepts considered for the intelligence module (IM) are shown in Figure 10. They include totally modularized, partially modularized, and totally integrated within the propulsion module. Several key studies were conducted to obtain data comparing these concepts. Consideration was given to the potential uses of a totally modularized intelligence module as a free-flying unit without the propulsion module. Additionally, consideration was given to use of the IM with other IPP elements either partially or in total. Other considerations include a comparison of performance penalties because of modularization and the relative ease of fabrication, checkout, and replacement of components. The totally modular concept was retained as a baseline during the study.

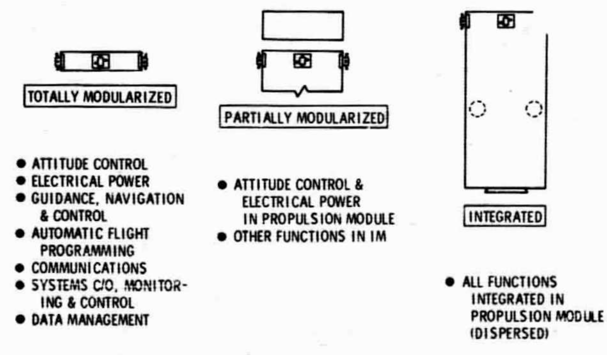


Figure 10. Intelligence Module Concepts Matrix

Concepts Evaluation

Several tradeoff studies were conducted during the first phase to obtain data for evaluation of the several concepts and for selection of up to three of these for the second phase studies.

The areas of evaluation included economics, growth potential and versatility, operations complexity, and risk.

Total program cost was considered in comparing the various concepts, and both the baseline program model and several variations to this model were considered. Growth potential and versatility evaluation considered the ability of the concepts to conduct missions of greater difficulty within the classes of missions already considered for the tug, as well as the ability to conduct missions beyond those currently defined. Operations complexity evaluation considered mission success, the complexity of space operations, and the ability to launch the tugs into earth orbit already integrated inside of the EOS. The final category, risk, was based on the sensitivity of concept to growth in system inert weight. Technology risks were not considered pertinent since all concepts utilize similar technology. Furthermore, the technologies characterized by the EOS and space station appear to provide a sufficient base for development of the space tug.

Figure 11 compares the total program cost for the concepts under consideration, including the breakdown in cost related to each program area. These data assume space basing of the tug and include the cost of delivering the tugs to the location where the mission originates, delivery of propellants consumed by the tugs, and the cost per mission for tug hardware assuming 10 reuses for the high characteristic velocity missions and 50 reuses for the low characteristic velocity missions. The cost of space tug payloads and their delivery is not included in these costs. These data indicate that only concepts 6 and 7 show relatively large increases in program cost compared to the other concepts. Their large program costs are caused by the necessity to expend all or part of the tug on the geosynchronous and planetary missions. Concept 6 is lower in cost than concept 7 because only a stage without an intelligence module is expended for the geosynchronous and near planetary missions. Concept 7 expends a stage and an intelligence module for these missions.

All other concepts are comparable in total program cost. Concept 11, which expends a tank set for the geosynchronous and near planetary missions, shows a program cost comparable to the fully recoverable versions. The recurring cost of the tank set and the saved propellants trade off favorably. The small stage [8800 pounds (4,000 kg)] also reduces the costs of conducting the low delta V missions.

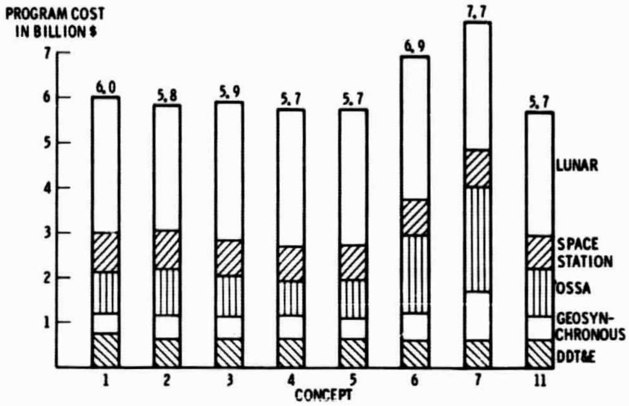


Figure 11. Space Tug 10-Year Total Program Costs

In order to determine whether the program costs for the concepts are sensitive to the baseline assumptions, sensitivity data were obtained by varying the assumed values. The number of propulsion module reuses varied between 10 and 30 for the high delta V missions and between 50 and 150 for the low delta V missions. Traffic model variations included the following: (1) a low, stretched-out program, (2) a high program, which had a 50-percent increase in OSSA mission traffic, and (3) independent assessments of cost in each mission category. Additionally, EOS and cislunar shuttle delivery costs varied by ±33 percent. The results of the sensitivity studies did not change the relative positions of the concepts. As a result of the economic analysis, only concepts 6 and 7 were eliminated. For this reason, several options still existed following the economic evaluation, and the selection of concepts requires considerations in other categories.

In the category of growth potential (payload within mission categories), it was found that concept 1 (designed for recoverable single stage geosynchronous payload insertion) had significantly greater capability than the other concepts. This is attributed to its large propellant loading as compared to the other concepts. For example, when used in a two-stage mode, it can inject

48,000 pounds (21,800 kg) to geosynchronous orbit, 54,000 pounds (24,800 kg) to the inner planets, and 23,000 pounds (10,400 kg) to the outer planets. When considering the category of growth potential (alternate mission capability), a similar result is obtained. For example, concept 1 can carry a 12,500 pound (5700 kg) payload round trip to geosynchronous orbit and can retrieve a 16,800 pound (7600 kg) payload from geosynchronous orbit. The round-trip capability would allow the potential for manned geosynchronous missions which require a 10,000 pound (4540 kg) round-trip capability.

Operational data obtained from timelines were used to determine the relative complexity of operations for the various concepts. Three categories of data were employed in evaluating the concepts: (1) the number of modules required to conduct operations, (2) the number of dockings required to conduct operations, and (3) the number of EOS launches required to conduct operations. An analysis of these data indicated that concepts 1 and 11 resulted in the least complex operations and that concepts 2 and 3 were the most complex operationally because they required assembly of tank sets with a propulsion module on orbit. This was required because the fully integrated concepts did not fit within the available 60-foot (18.2 m) EOS bay length restriction.

Phase I Recommendations

As a result of the Phase I studies, it was recommended that three propulsion module concepts be selected for study during the second phase. These concepts were:

1. Concept 1 - which originated from reusable single stage accomplishment of the geosynchronous mission. The propellant loading of this concept is 80,000 pounds (36,200 kg).

2. Concept 2 - which originated from reusable two-stage accomplishment of the geosynchronous mission. The propellant loading of this concept is 36,000 pounds per stage (16,300 kg).

3. Concept 11 - which accomplished the geosynchronous mission by expending a tank at insertion of the payload but allowed recovery of the small propulsion module and the intelligence module. The propulsion module propellant loading is 9000 pounds (4,100 kg) and the tank set propellant loading is 48,000 pounds (21,800 kg).

PHASE II SUMMARY

During the second phase of the study, the three concepts selected as a result of the Phase I studies were studied in greater detail to refine the mission and operations data related to their use (including implications of ground and space basing on operations and performance, and the definition of their capabilities for performing all of the integrated program plan mission objectives). The mission and operations refinement studies resulted in the determination of program buildup data, performance data, and operational tradeoff data. These data were used to refine the concept designs, to establish planning data, and to develop economic tradeoff data comparing these concepts.

The design refinement studies were directed toward a more critical examination of the design characteristics of the concepts. These included layouts of the various modules (including placement of subsystems and module interfaces), several key subsystem tradeoff studies, and estimation of the effects of changes to a baseline concept on mass properties, concept size and cost. These data were utilized in the mission and operations refinement studies to relate performance sensitivity to concept variations. They also were used as a baseline to produce the planning data and to assess the relative economics of the concepts and the influences of variations in the baseline on space tug economics.

The economic study resulted in a comparison of the reusable concepts in performing the matrix of missions and sensitivity of these results to variations in the baseline concept characteristics and mission characteristics, including the impact of shuttle payload capability and propellant resupply costs. Comparisons also were made between reusable and expendable concepts.

Concepts Descriptions

During the initial portion of Phase II, the three selected concepts were resized, based on refined subsystems and design data, to accomplish the 10,000 pounds (4540 kg) geosynchronous payload insertion mission. The results of this resizing of the baseline concepts are shown in Figure 12, which indicates the propellant capacity, gross weight (including the 10,000-pound (4540 kg) payload), and the length of the propulsion and intelligence modules when organized to accomplish the geosynchronous injection mission. The resizing resulted in a slight reduction in size for concept 1 and an increase in size for concepts 5 and 11.

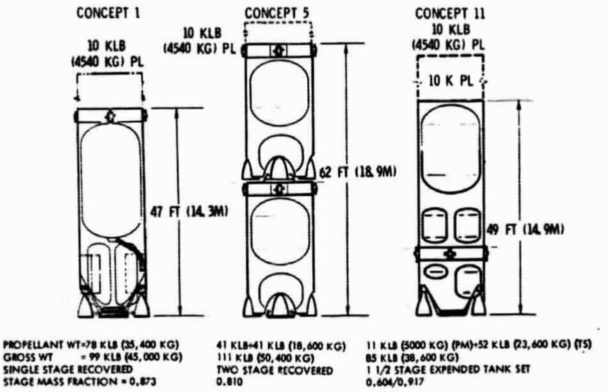


Figure 12. Reusable Geosynchronous Mission Space Tug Concepts

The primary design characteristics of concepts 1 and 11 are shown in Figure 13 (concept 5 is similar to 1 except it is smaller). The propulsion modules have four high-chamber-pressure engines located around a central aft Apollo-type docking gear. The four engines provide redundancy with an engine out and also help to reduce stage length. The single hydrogen tank allows the simplest, lowest-weight, and least-length packaging arrangement. The four oxygen tanks were selected on the basis of integration with the four engines. They allow common load paths for the engines and oxygen tanks. The structure is non-integral, although integral structure was considered as an alternative.

The intelligence module is designed for autonomous space-based operations, and the baseline is a completely modular system. This module contains all of the components necessary to conduct unmanned missions when combined with the propulsion module, or to conduct manned missions when combined with the propulsion module and crew module. Because the baseline system assumes space basing, more than one level of redundancy is provided for some of the key components to assure that the missions may be accomplished with little or no servicing.

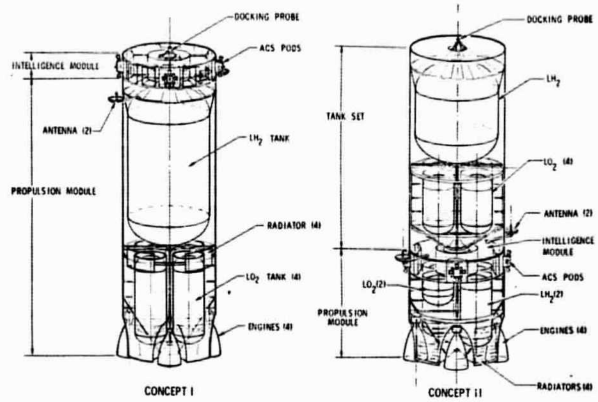


Figure 13. Design Characteristics of Concepts 1 and 11

The baseline crew module is a vertical cylinder 15 feet (4.6 M) in diameter and 8 feet (2.4 m) in height. The free volume is sufficient for a 4-man, 28-day lunar surface mission. This crew module is oversized for routine, low-earth-orbit space station support missions.

The baseline design is not necessarily optimum, and several variations to this design, shown in Table 1, have been considered to establish their

Table 1. Variations to Baseline

VARIATIONS	PRIMARY DESIGN INFLUENCES: INERT WEIGHT	LENGTH	SPECIFIC IMPULSE	OTHER
NUMBER OF ENGINES - 1, 2, $\boxed{4}$	✓	✓	✓	DOCKING GEAR & O_2 TANK ARRANGE.
BASING - $\boxed{\text{SPACE-BASED WITH PF}}$, SPACE-BASED (EOS FUELING), GROUND-BASED	✓ (INSULATION & REDUNDANCY)			EOS INTERFACES, OVERALL OPERATIONS
TANKAGE - 1, 2, $\boxed{4}$ LO_2 TANKS	✓	✓		NUMBER & ARRANGE. OF ENGINES
DOCKING GEAR - $\boxed{\text{APOLLO-TYPES}}$, NEUTER (ACTIVE, PASSIVE), OTHER	✓	✓		NUMBER OF ENGINES & INTERFACES WITH OTHER IPP ELEMENTS
IM MODULARITY - $\boxed{\text{TOTALLY MODULAR}}$, MODULAR AVIONICS, TOTALLY INTEG	✓			IM USES, SERVICING
AUTONOMY - $\boxed{\text{MAXIMUM AUTONOMY}}$, MODERATE AUT, NONAUT	✓			MISSION SUPPORT & MISSION CAPABILITY
TECHNOLOGY BASE - $\boxed{\text{EOS/SPACE STN}}$, ADVANCED TECHNOLOGY	✓		✓	
PM STRUCTURE - $\boxed{\text{NON-INTEGRAL}}$, INTEGRAL	✓			INSULATION APPROACH

$\boxed{}$ INDICATES BASELINE effect on gross weight, length, operational characteristics, and other factors. Several of the variations are specifically design oriented, such as number of engines, number of LO_2 tanks, docking gear, and PM structure. Others are operational variations that influence design, such as basing and autonomy. Although earth orbital shuttle and space station technology has been assumed for the baseline, the impact of utilizing more advanced (but realizable) technology also has been considered.

Concept Comparisons

The three selected concepts were re-evaluated during Phase II in a manner similar to the Phase I evaluation. Figure 14 compares the total program costs for a space-based concept. This figure indicates that the total program costs are similar. The development costs for all concepts were nearly the same and include a three-phase program to develop the entire space tug capability: (1) unmanned earth orbital ($560-million), (2) manned earth orbital ($390-million), and (3) manned lunar landing ($520-million).

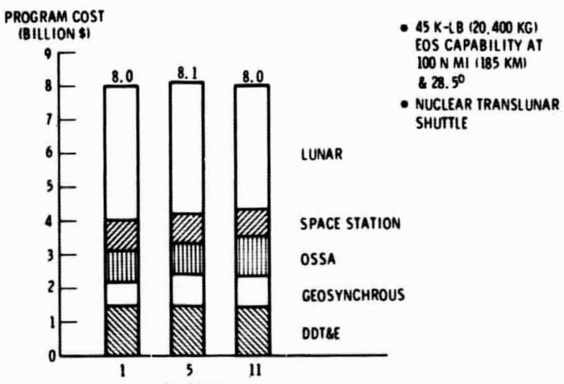


Figure 14. Space Tug 10-Year Total Program Costs (Space-Based)

Elimination from consideration of the lunar landing mission would tend to favor concept 1 economically. Consideration of only high-energy missions such as geosynchronous and other OSSA missions also would favor concept 1; whereas the low performance space station support missions favor concept 11, which uses only its small propulsion module for these missions.

If ground basing is considered for the geosynchronous and other OSSA missions, it was found that concept 5 mission costs would be considerably higher than those of concepts 1 and 11. This increase in cost is due to the excessive length of concept 5, which requires two shuttle launches to accomplish the mission. Whether space-based or ground-based, it was found that the operations for concept 5 were considerably more complex than for concepts 1 and 11 because of the two-stage operations required for high-energy missions.

When comparing the sensitivity of the concepts to growth in stage inert weight, it was found that concept 11 was least sensitive (6.8 pounds of propellant per pound of inert weight). Concept 1 showed a growth of 7.5 pounds of propellant per pound of inert weight. Although the sensitivity of concept 5 is less per stage than the other two concepts (4.4 pounds of propellant per pound of inert weight), the requirement to use two stages for high-energy missions results in the highest total sensitivity (8.8 pounds of propellant per pound of inert weight).

Space Tug Evolution

All of the previous data have been based on a set of baseline mission model, space tug design, and earth orbital shuttle characteristics. The effects on the space tug of varying some of the basic assumptions are described in this section. Some of the more important considerations are: (1) basing concept, (2) mission model impacts, (3) effects of autonomy and technology (specifically on space tug avionics), and (4) the effects of earth orbital shuttle characteristics.

In the following sections, these considerations will be discussed and potentially attractive space tug evolutionary routes will be described.

Basing Concept Implications

An investigation of mission models indicates that space tug missions originating from low earth orbit tend to group into two major initial inclinations: (1) 28.5 to 33 degrees for geosynchronous, planetary, and earth orbit-to-lunar orbit logistics and (2) 55 degrees for space station support missions. A small percent of the missions fall into an "odd-orbit" category and many of these are near-polar inclination missions (many near-polar inclination missions are insufficiently low earth orbits to allow accomplishment by the EOS alone).

In accomplishing many of the OSSA and DOD missions (planetary and geosynchronous), the space tug originates its mission from 28.5 degrees and may be either space-based or ground-based. The odd-orbit missions generally would require large plane changes to be made for mission initiation from either 28.5 or 55-degree inclinations and these missions are best accomplished in a ground-based mode to allow coplanar space operations.

Because of the routine nature of the space station service missions (payload transfer, experiment servicing and placement, and assembly operations), the space tug should be space-based.

Because of the remote location of lunar landing missions, the space tug must be space-based for these missions. The routine nature of low earth orbit missions in support of lunar missions (translunar shuttle station keeping, propellant transfer, crew transfer, and cargo transfer) also requires a space-based operation.

Ground or space-basing of the tug has several implications on the tug itself, on the shuttle, and on other systems. The baseline space tug design is constrained to be space-based. The result of space-basing is to require a high degree of reliability/redundancy to assure that routine operations can be conducted in a timely manner without the need for refurbishment or servicing, other than the replenishment of propellants. Additionally, space basing implies a greater degree of autonomy to allow routine and relatively complex operations with minimum command inputs to the tug. These requirements lead to high avionic component weights which compromise a large percent of the total space tug inert weight and an even larger percent of the space tug unit cost. Use of a space-based mode does, however, decrease the space tug dependence on earth orbital shuttle size as compared to ground-basing. Economics appear to be dependent on EOS size whether ground or space-basing is utilized. If the EOS is used directly as a refueling tanker, it must be capable of routine propellant transfer operations. Alternatively, space basing may require an orbiting propellant facility.

Ground-basing relatively decreases reliability/redundancy requirements and the degree of autonomy desired. These reductions are made possible by routine servicing after each mission on the ground and the relative ease of preparing the system sequencing and data for the next mission on the ground. Because the tug must be carried up in the shuttle, preferably fully fueled and with the payload integrated, the gross weight and length of the tug must be compatible with shuttle capabilities. Otherwise, complex on-orbit operations involving fueling, payload integration, and multiple shuttle flights would be involved. Ground-basing for the OSSA and DOD missions leads to a large shuttle payload capability and full use of the current cargo bay (15-foot diameter by 60-foot length (4.6 m diameter by 18.3 m length)). Larger bay dimensions would be desired from a tug viewpoint. Ground-basing would require electrical, mechanical, and fluid interfaces with the shuttle. Minimum electrical connections would provide assessment of the tug status to the shuttle. Mechanical connections would be necessary for attachment in the bay and to the payload handling equipment. Fluid interfaces would require a closely integrated shuttle and tug development. Although the space tug may be ground-based for some missions, the ability to achieve space-basing when necessary does not appear to be prohibitive.

Mission Model Implications

Previous data have been presented on the basis of certain space tug mission assumptions. One of the key ground rules in sizing the space tug is the requirement to insert up to 10,000 pounds (4540 kg) to geosynchronous equatorial orbit. Since this payload requirement sized all of the concepts, the effect of this ground rule on space tug characteristics is of interest. Furthermore, a large percent of the space tug missions were in support of the space station and lunar programs. The impact on the tug of eliminating one or the other of these requirements also would be of interest.

Figure 15 illustrates the distribution of number of payloads as a function of payload weight for DOD and NASA geosynchronous missions. These data indicate that most payloads are considerably less than the design constraint of 10,000 pounds (4540 kg). A design based on 7000 pounds (3180 kg) would be capable of emplacing about 95 percent of the payloads. A 5000 lb (2270 kg) design could emplace about 92 percent of the payloads, and a 3000 pound (1360 kg) design could emplace about 85 percent of the payloads. This suggests the possibility of designing the space tug for reusable injection of payloads less than 10,000 pounds (4,540 kg) and the occasional expenditure of the tug for injection of large payloads. The effect of reducing payload is to reduce gross weight by a ratio of 3.5 pounds per pound of payload weight for concept 1. A reduction of payload from 10,000 pounds (4540 kg) to 5000 pounds (2,270 kg) reduces gross weight by 17,500 pounds (7,900 kg).

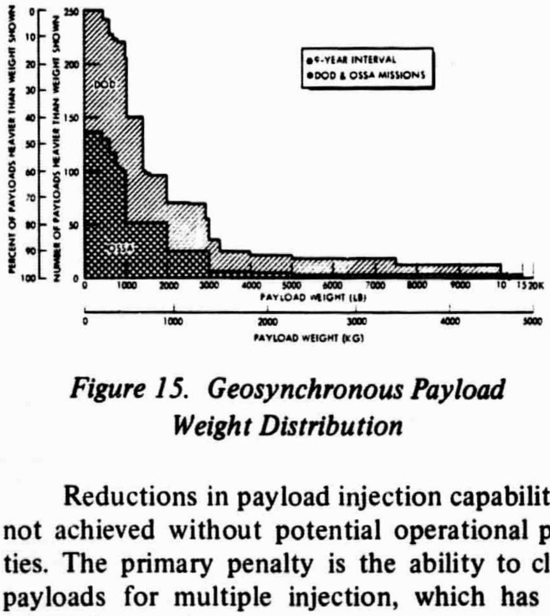


Figure 15. Geosynchronous Payload Weight Distribution

Reductions in payload injection capability are not achieved without potential operational penalties. The primary penalty is the ability to cluster payloads for multiple injection, which has been assumed in reducing the number of geosynchronous missions to 43. A vehicle sized to carry a single 10,000 pound (4540 kg) payload to synchronous orbit can inject two payloads weighing 3450 pounds (1520 kg) each in orbits separated by 180 degrees for a 90-hour phasing time. Reduction of single payload insertion capability to 5000 pounds (2260 kg) reduces the capability to 850 pounds (380 kg) per payload. This virtually eliminates the capability for multiple payload insertion.

The entire area of multiple payload insertion requires considerable study to establish the capability for clustering within the confines of the EOS bay. This study requires more discrete data on payload dimensions and tradeoffs on space tug insertion capability.

Effect of Autonomy and Basing on Subsystems

The baseline system described previously was designed to be space-based with maximum autonomy and utilized shuttle and space station technology. Because of the potential interest in ground-basing for many of the space tug missions, the effect of the resulting changes on subsystems requirements and weights is of interest. Additionally, the influence of various degrees of autonomy on subsystems weight and the potential weight reductions that may be possible by utilizing advanced technology subsystems is also of interest. Since these subsystems compose a large percentage of the space tug inert weight, it may be anticipated that weight reductions in this area would have a significant impact on tug size, weight, and cost.

Figure 16 illustrates the effect of these factors on subsystems weights, propellant requirements, gross weight, unit cost, and cost per mission for the geosynchronous mission. The differences in capability implied by maximum, medium, and minimum autonomy are as follows: (1) maximum

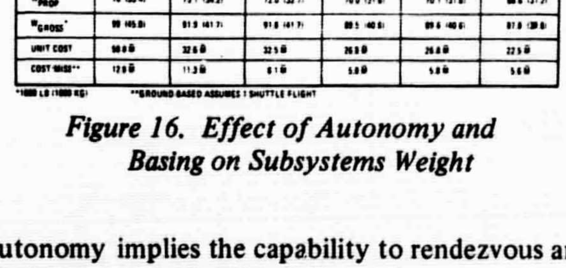


Figure 16. Effect of Autonomy and Basing on Subsystems Weight

autonomy implies the capability to rendezvous and dock automatically, the ability to initiate a mission by communicating only the target ephemeris, and the ability to conduct a self checkout; (2) medium auton my implies the same capability except that autom...ic rendezvous and docking sensors and associated memory are removed (control in this phase by another external system is necessary); and (3) minimum autonomy implies a less precise navigation capability which degrades injection accuracy and requires ground tracking and communication for mission accomplishment as well as the removal of capability implied by medium autonomy.

The primary difference between space and ground-based subsystems is the reduction in redundancy because of the ability to check out and replace components on the ground between missions. The data shown in Figure 16 indicate that a large decrease in subsystems weight is associated with ground-basing. The related large change in unit cost is attributable to the large cost factors applied to avionics subsystems [about $22,000 per pound ($48,000 per kg)]. The effects on gross weight of basing also is rather large [from 99,000 pounds (45,000 kg) gross weight to 91,800 pounds (41,700 kg)].

Use of technology advanced beyond EOS/EOSS technology in the computer hardware and software, guidance and navigation hardware, and communications hardware also leads to large reductions in subsystems weight. A thorough discussion of these changes is given in the subsystems portion of the final report (Volume 5).

First-unit costs used as a baseline are considered to be conservative values. The effect of several variables (first-unit cost, number of reuses, basing concept, and EOS size) on the total 10-year geosynchronous mission cost are shown in Figure 17. These data include a refurbishment cost of 3 percent of first-unit cost for each mission for ground-based operations and 3 percent of first-unit cost for each 10 missions for space-based operations. These data indicate that the total program cost becomes relatively insensitive to unit cost and number of reuses as the number of reuses approaches 25 to 30. The payload capability of the shuttle at 100 nautical miles (185 km) and 28.5 degrees is shown to have a large impact on program cost.

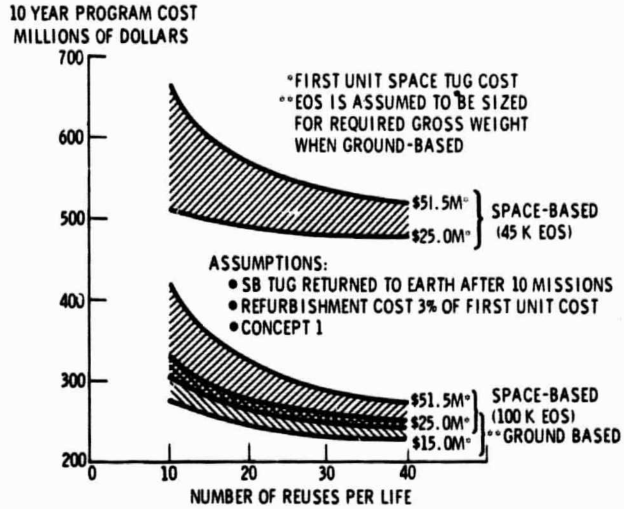


Figure 17. Effect of Number of Reuses, Space Tug Unit Cost, Basing Concept and Shuttle Size on Geosynchronous Mission Cost

Effect of EOS Characteristics

Although EOS payload weight capability and bay dimensions are significant concept drivers for the space tug, particularly when ground-based operations are considered, the manner in which cargo is handled and the ability of the shuttle and tug to share the shuttle orbital maneuvering system (OMS) propellants necessary for an abort during ascent also are very significant to the design.

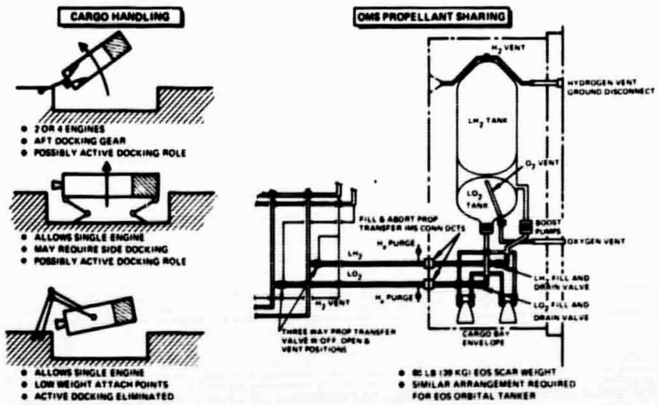


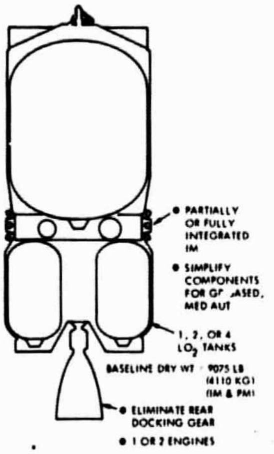
Figure 18. Effect of EOS Characteristics on Tug

Three of the cargo handling concepts being studied for the EOS are illustrated in Figure 18.

The first requires that the tug be docked at the aft end. This results in multiple engines on the tug or alternatively a very large docking gear around a single engine, both of which lead to large weight penalties. The second concept implies the need for docking on the side of the tug, but allows the use of a single engine. The third concept utilizes manipulators to remove and insert cargo into the bay. This concept eliminates the requirement for active docking by the tug entirely (only stabilization is necessary). It also allows use of a single engine. This last approach appears to have significant advantages from a space tug point of view. Under any circumstances, provisions are necessary for fastening the space tug in the bay to react normal and lateral loads induced during launch, reentry, and landing.

During ascent to orbit, the current shuttle design requires up to 25,000 pounds (11,300 kg) of propellant in the OMS to be used in the event of an engine failure in the orbiter stage. During a normal mission, this propellant is available on orbit. Since this system and the tug both use LO_2/LH_2 propellants, the possibility exists of sharing these propellants with the tug to increase the payload capability of the shuttle by 25,000 pounds (11,300 kg). Two concepts may be used to allow this sharing. One would require the shuttle to pump the propellants into an off-loaded tug when on orbit. In the other concept, the tug is fully loaded with propellants and the OMS propellants are obtained from the tug only in the event of an abort. A schematic of interconnecting plumbing is shown in Figure 18. The resulting EOS scar weight is only 86 pounds (39 kg). This concept also could apply to the EOS when it conducts routine orbital propellant tanker missions.

As a result of varying from a rear docking requirement (assuming compatible EOS cargo handling), several simplifications of the baseline design are possible. Some of these are indicated in Figure 19 for concept 1. Removal of the rear docking gear and replacement of the four engines by one leads to a 560-pound (250 kg) inert weight reduction and 0.9-foot (0.27 m) length increase if four LO_2 tanks are used and a 910-pound (410 kg) weight decrease and 5.2-foot (1.6 m) length increase if a single LO_2 tank is used. Furthermore, total integration of the IM components into the PM reduces weight by 400-pounds (180 kg), and retention of modular avionics only reduces weight by 200 pounds (90 kg). Ground-basing with medium autonomy could reduce inert weight by about 1050 pounds (465 kg). Use of advanced avionics technology and ground-basing reduces inert weight by 1060 pounds (470 kg).



CHANGE	ΔW, LB (KG)	ΔL, FT (M)
2 ENG, 2 LO_2 TANKS, NO AFT DOCKING	-410 (-190)	+1.2 (0.37)
1 ENG, 4 LO_2 TANKS, NO AFT DOCKING	-560 (-250)	+0.9 (0.27)
1 ENG, 1 LO_2 TANK, NO AFT DOCKING	-910 (-410)	+5.2 (1.6)
TOTALLY INTEG IM COMPONENTS	-400 (-180)	-3.8 (1.2)
MODULAR AVIONICS ONLY	-200 (-90)	-3.4 (1.0)
GRD-BASED, MED AUTONOMY	-1050 (-480)	-2.1 (0.64)
GRD-BASED, MAX AUTONOMY, ADV AVIONICS	-1060 (480)	-2.1 (0.64)

1′ DRY WT 6265 LB (2840 KG), FIRST UNIT ≈ \$25M, W_{PROP} 63,000 LB (28,000 KG)

1″ DRY WT 6605 LB (3000 KG), FIRST UNIT ≈ \$26M, W_P 64,400 LB (29,100 KG)

Figure 19. Potential Simplification of Baseline

Some of these changes to the baseline were combined to establish two simplified concept 1 designs (1′ and 1″). In concepts 1′ and 1″, the changes from the baseline are indicated by the shaded areas in Figure 19. The result of these changes is to reduce propellant requirements from 78,000 pounds (35,300 kg) for the baseline design to 63,000 pounds (28,600 kg) for concept 1′ and 64,400 pounds (29,100 kg) for concept 1″. Dry weight also is reduced significantly.

The unit recurring cost reduction also was calculated and the major change in unit cost is attributable to a reduction in expensive avionic system components. The first unit cost was reduced from about \$50-million for the baseline concept to \$25-million for concept 1′ and \$26-million for concept 1″. The reduction for concept 1′ assumed that the advanced avionics components have the same cost per unit weight as the EOS/EOSS-type components. Considerable additional study is required to determine a valid cost for the advanced components.

Whereas the baseline single-stage recoverable system has a gross weight of 99,000 pounds

(44,900 kg) including a 10,000-pound (4540 kg) payload, the inert weight changes in concepts 1′ and 1″ result in gross weights of 80,000 pounds (36,300 kg) and 82,000 pounds (37,200 kg), respectively. Dependent upon choice of concept approach, the shuttle payload requirement at 28.5 degrees and 100 nautical miles (185 km) could vary between 80,000 and 99,000 pounds (36,300 kg and 44,900 kg). Utilization of OMS propellant sharing reduces this requirement to between 55,000 and 74,000 pounds (25,000 kg and 33,600 kg) assuming that 25,000 pounds (11,300 kg) of OMS propellants can be shared.

Potential Evolutionary Approaches

Figure 20 indicates a potential evolutionary approach for the space tug system, indicating the buildup of capabilities ranging from initial operations to the lunar landing mission.

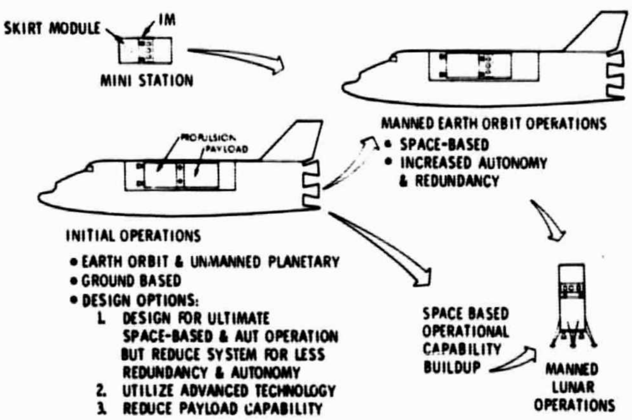


Figure 20. Space Tug Evolution

Initial operations of the propulsion and intelligence modules will probably be ground-based and unmanned. The tug will be used for the missions in earth orbit outside the range of EOS capability and also will be used for planetary injection missions. The crew module may evolve as an earth orbital mini-station. Initially, it may be used in the shuttle bay, but later missions may be conducted in a free-flying configuration.

Together, the crew module, propulsion module, and intelligence module will eventually provide a manned on-orbit capability for assembly, payload transfer, crew transfer, experiment servicing, and other support missions. During this time, the capability of conducting space-based operations will be attained. These capabilities will then allow manned lunar operations. To achieve this final capability, the space tug requires addition of the lunar landing kit and cargo pods and several changes to the propulsion and intelligence modules to allow lunar landing mission capability.

Because of the impact of stage inert weight on gross weight for the high-energy geosynchronous and planetary missions, it is important that the inert weight of the tug be minimized to assure compatibility with the shuttle payload capability when ground-based. As shown previously, this may be accomplished in several ways: single engine design without rear docking, reduction in avionics components weights by reducing redundancy and autonomy or utilizing advanced technology, by partial or total integration of the intelligence module components into the propulsion module, and by utilizing OMS propellant sharing. Elimination of rear docking and resulting single engine design is contingent upon shuttle design philosophy. OMS propellant sharing also is heavily dependent on shuttle design philosophy. Considerable detailed subsystems design analysis is necessary to determine the practicality of evolving from a comparatively simple ground-based avionics system to a fully autonomous space-based capability without invoking a major design change when space-basing is required. To critically determine the benefits and costs associated with advanced avionics technology, research studies specifically aimed at a definition of the design approaches are necessary.

Although partial or total integration of the IM components into the propulsion module reduces inert weight, it also eliminates potentially-attractive uses of a totally modular approach. For example, the mini-station concept requires only the IM and a small skirt module that contains LO_2/LH_2 for power, life-support, and attitude control. This small system, when attached to the crew module and experiment modules, could fit into the cargo bay to accomplish manned missions in any orbit. This implies a desire to either have a totally modular IM or, at a minimum, an IM containing at least the avionics.

Concepts that allow integrated avionics and tankage in a submodule that may be used for mini-station type missions have been considered and appear to be consistent with the single-stage concept 1. The small propulsion module of concept 11 (1-1/2 stage) is already compatible with this requirement.

A final approach to reducing the gross weight of the tug in the shuttle for ground-basing operations is to reduce the design payload requirement to less than 10,000 pounds (4,540 kg). As shown, this may inhibit multiple payload injection.

Additional, closely coupled shuttle and tug design studies are necessary to fully develop the most feasible evolutionary approach and to assure shuttle/tug compatibility. Since advanced avionics may allow a low-weight, fully-autonomous approach, studies related to these systems also are keys to developing the most desirable approach.

Figure 21 summarizes the preliminary space tug development schedule and is consistent with the overall evolutionary approach discussed previously and the operational dates defined in the mission model.

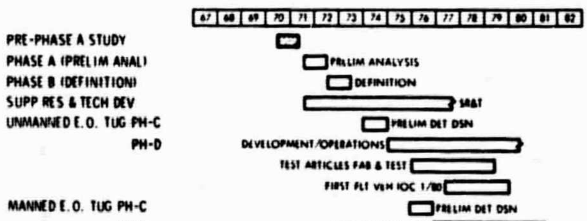


Figure 21. Preliminary Program Development Summary Schedule

Figure 22 summarizes the annual costs for development and production. Development costs are shown for each of the three development categories. Although this figure is specifically for concept 1, the development costs of the other concepts are similar. Peak program costs for hardware development and procurement occur between 1978 and 1980 and are $450-million. Peak development cost occurs in 1978 and is $300-million. Total development cost is $1.47-billion. Of this total, $560-million is for the unmanned earth orbital development, $390-million is for manned earth orbital development, and $520-million is for lunar mission development.

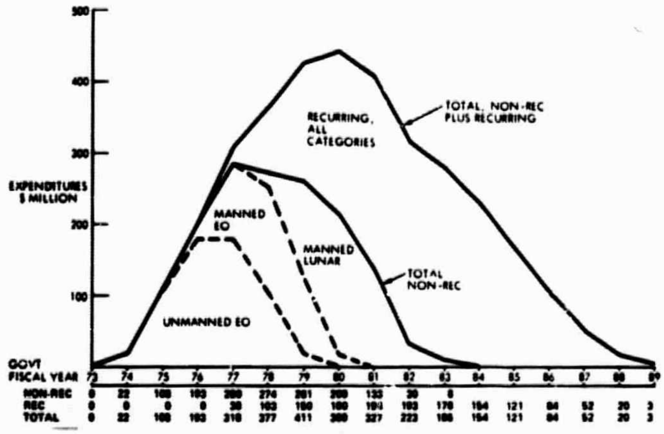


Figure 22. Design Concept No. 1 Annual Funding Requirements

Comparison of Space Tug and Other Systems

Alternative system or operational approaches have been considered in the several mission areas studied for the space tug. In the low earth orbit space station support area, the alternatives for payload delivery have included direct EOS delivery to the space station and transfer of payloads between a low parking orbit [e.g., 100 nautical miles (185 km)] and the space station by the tug. A comparison of these modes indicates a 30 percent increase in net delivered payload (propellants used by the tug in transferring the payload are subtracted from the payload) when the tug payload transfer mode is used.

Most operational studies of space station experiment modules have assumed that the space tug does not exist to aid in their placement and maintenance. As a result, these studies have led to the definition of a requirement for propulsive experiment modules. This leads to additional complexity and cost for each of the modules. Studies of space tug deployment and servicing have shown that a single tug based at the space station can provide this function and that the total propellant required for the servicing and placement cycle is 280 pounds (127 kg).

During the first few years of the space station program, sufficient propellants are available from the EOS orbital maneuvering system [assuming the EOS retains a 100 nautical mile (185 km) parking altitude for payload transfer] for all of the space station tug missions. During the later years of the program (space base), an excess of up to 550,000 pounds (228,000 kg) exists. This excess might be used to launch planetary missions from the space station rather than 28.5 degrees inclination.

The prime competitive approaches for conducting the geosynchronous missions include the use of expendable LO_2/LH_2 or earth storable stages or the use of a reusable space tug. In the next several paragraphs, the primary comparison issues will be discussed. These include economic comparisons of these systems for insertion of payloads up to 10,000 pounds (4540 kg) as well as the economic aspects of payload retrieval from geosynchronous conditions.

As will be explained, the use of the EOS orbital maneuvering system propellants also has a significant effect on economics. These LO_2/LH_2 propellants [up to 25,000 pounds (11,300 kg)] would be available on orbit for transfer to the space tug for a normal EOS mission since they are contingency propellants required for an abort to orbit in the event of an engine failure in the second stage during ascent. In essence, the ability to utilize these propellants is equivalent to increasing the payload capability of the earth orbital shuttle by 25,000 pounds (11,300 kg).

A reusable space tug designed to insert 10,000 pounds (4,540 kg) of payload at geosynchronous equatorial conditions also has the capability of retrieving large payloads. For example, concept 1 can retrieve about 3900 pounds (1,770 kg) of payload operating as a single stage.

A brief analysis was made of satellite malfunction rates at times soon after their insertion, and it was estimated that the failure rate was at least 5 percent and perhaps as high as 10 percent. An analysis of the cost per pound of satellites (Surveyor, Nimbus, Orbiter, Mariner II and IV, OSO, OGO, BIO, Ranger, and OAO) indicated a range between $20,000 and $90,000 per pound ($44,000 and $198,000 per kg). The lower bound of these data, a nominal satellite weight of 2000 pounds (9050 kg), a failure rate of 5 percent, and a retrieval cost of $5000 per pound ($11,000 per kg) were assumed to determine the cost savings for the baseline NASA geosynchronous program. The $5000 per pound ($11,000 per kg) for retrieval cost is based on an analysis of payload recovery presented in the Technical Summary (Volume 2). The net saving is $15,000 per pound ($33,000 per kg). Based on the geosynchronous mission model, the total ten-year program savings due to payload recovery is about $250-million.

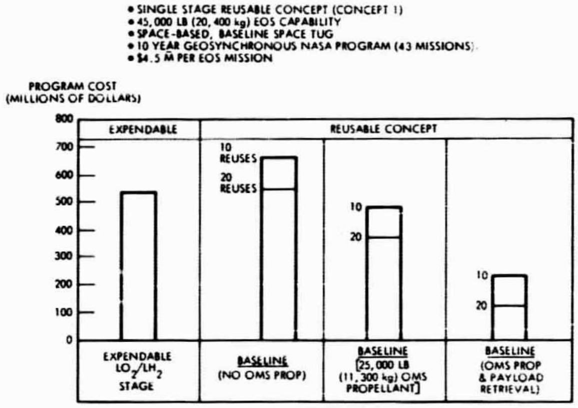


Figure 23. Comparative Cost of Geosynchronous Mission for Space-Based Reusable and Expendable Concepts

A comparison of the total ten-year NASA geosynchronous mission costs for expendable kick stages and space-based reusable systems is shown in Figure 23. A shuttle payload capability of 45,000 pounds (20,400 kg) at 28.5 degrees and 100 nautical miles (185 km) was assumed for calculating the reusable concept propellant resupply costs. A comparison of the baseline design with maximum autonomy to the expendable system indicates comparable program cost for a tug that is reused 20 times. If 25,000 pounds (11,400 kg) of orbital maneuvering system propellant are utilized by the reusable system (this essentially increases the EOS payload capability by the OMS propellant weight), the reusable system cost drops from $550-million to $370-million. Inclusion of the cost savings potentially available from retrieval of malfunctioning geosynchronous payloads reduces the program cost to $120-million.

Figure 24 compares the geosynchronous program costs of expendable concepts and three versions of a ground-based reusable space tug. The earth orbital shuttle payload capability is assumed to be consistent with the required gross weight shown for each concept. This figure indicates that the ground-based reusable systems show a substantial program cost reduction when compared to the expendable system. When the estimated cost savings for payload retrieval is included, the program cost is reduced nearly to zero. All of the reusable concepts have comparable program costs, but the required EOS payload capability varies from 80,500 pounds (36,500 kg) to 92,000 pounds (41,800 kg) as the design is varied, assuming that the EOS orbital maneuvering system propellants are not utilized. Required EOS capability would be 25,000 pounds (11,300 kg) less if the OMS propellants were utilized.

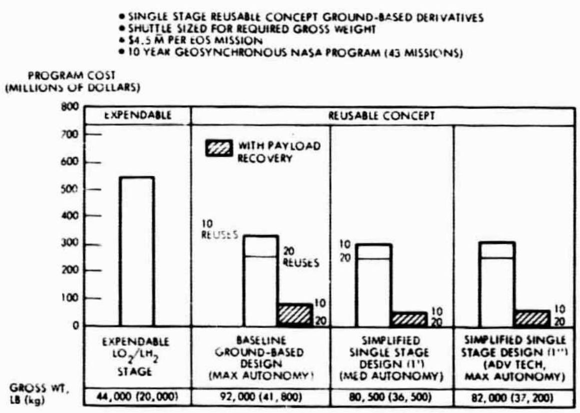


Figure 24. Comparative Cost of Geosynchronous Mission for Ground-Based Reusable and Expendable Concepts

These data show that the space tug can accomplish the geosynchronous mission on a basis at least comparable to expendable stages when a 45,000-pound (20,400 kg) EOS capability at 28.5 degrees and 100 nautical miles (185 km) is assumed. At this size shuttle capacity, inclusion of payload retrieval savings and use of the OMS propellants significantly reduces the reusable system cost. Increasing the EOS capability to allow single EOS- flight, ground-based space tug missions leads to even greater economic benefits.

CONCLUSIONS

As a result of this study, it was determined that the performance requirements of the geosynchronous equatorial mission provided the main driver for sizing of the space tug propulsion module. Several concepts were studied during Phase I and three of these concepts were selected for a more detailed analysis during the second phase of the study. These three concepts were sized by the geosynchronous mission.

When applied to other earth orbital missions, the selected concepts were found to provide satisfactory performance capability. Even though the large, single-stage reusable concept was oversized for the low-earth-orbit support missions, off-loading propellants in the large stage lead to performance characteristics 15 percent less than for an optimized stage.

When these concepts were applied to the lunar landing mission, it was found that the crew module would provide improved functional characteristics if it were placed at the bottom of the stage rather than on the upper portion of the stage as it is in orbital operations. This tends to force the engines outboard to clear the crew module.

As a result, it was concluded that a multipurpose space tug is economically feasible for application to both the high and low performance earth orbital missions. However, this design would require a block change (like Apollo block 1 to block 2) for lunar missions.

When compared with other, potentially competitive concepts in each of the mission areas, the following was determined:

Space Station Support Missions

1. Use of the space tug for payload transfer between the shuttle and the space station increases the net delivered payload by at least 30 percent.

2. Use of the space tug to emplace, retrieve, and service experiment modules requires only 280 pounds (130 kg) of propellant each time and relieves the need for propulsive experiment modules.

Lunar Missions

1. An appropriately modified space tug has the performance capability to accomplish the lunar landing missions.

2. The space tug used in conjunction with chemical or nuclear cislunar shuttles as a second stage or earth orbit retrieval stage significantly increases performance capability for logistics between earth and lunar orbits. (Use of the space tug as a second stage on the chemical cislunar shuttle increases payload delivery efficiency by a factor of two.)

Geosynchronous Missions

1. A ground-based space tug is preferred for these missions, and it is more economical than an expendable kick stage. ($550-million total 10-year program cost for the expendable as compared to $250-million for the space tug.)

2. The ability of the space tug to retrieve malfunctioning satellites appears to provide an additional significant economic potential. (This reduces the ground-based geosynchronous 10-year program cost to nearly zero.)

3. Tug-utilization of the EOS orbital maneuvering system propellants significantly decreases propellant resupply cost for space-based operations or reduces the required EOS payload capability for ground-based operations.

As a result of this study, interfaces with all of the IPP systems were identified. The earth orbital shuttle is the key interfacing system for the space tug, particularly when use of the tug as a ground-based third stage is considered. In this case, not only are the payload bay dimensions important, but the payload weight capacity of the shuttles closely constrains the space tug design.

The current 15-foot (4.6 m) bay diameter is acceptable, but a smaller diameter would lead to increased tug length. Greater length would impact the lunar landing concept which is best in a low profile configuration. The current 60-feet (18.3 m) bay restriction is marginal and may reduce the potential for multiple geosynchronous payload injection missions. Increases in both length and diameter would relieve tug design constraints. A diameter increase would be most beneficial.

A shuttle sized to carry 45,000 pounds (20,400 kg) at 100 nautical miles (185 km) and 28.5 degrees does not allow the conduct of ground-based geosynchronous missions unless complex multiple-launch missions are staged. For the design concepts considered in this study, an EOS capability of between 80,000 and 99,000 pounds (36,300 and 44,900 kg) would be required for ground-basing if orbital maneuvering system (OMS) propellant sharing is not used. Use of OMS propellant sharing reduces the EOS payload capability requirement to between 55,000 and 74,000 pounds (25,000 and 33,600 kg) assuming that 25,000 pounds (11,200 kg) of OMS propellants are normally available for sharing. The LO_2 and LH_2 systems of the tug and the shuttle OMS would have to be plumbed together during ascent to allow sharing of the propellants either for EOS abort to orbit or use in the space tug for mission accomplishment.

The EOS docking and payload handling concept also affects the tug significantly. The so-called "cherry-picker" manipulator concept appears best suited for the tug. It allows the use of a single engine concept without the need for active docking avionic systems and docking mechanisms. This reduces the tug gross weight by about 6000 pounds (2,700 kg).

Of the three propulsion module approaches studied during Phase II, the most attractive was concept 1. This concept was economically comparable to other concepts, had the best growth potential, and was operationally simple. It was the only concept which had only one staging relationship for all missions (single stage).

Concept 11, which utilizes a 1-1/2 stage principle for high-energy missions, appears to have certain special advantages. The small propulsion module by itself is adequate for the low earth orbit missions and can be put into the shuttle bay with large payloads. It also has the lowest gross weight for the geosynchronous equatorial mission, which may be advantageous, dependent on EOS payload capability. Economic disadvantages resulting from tank set expenditures during high-energy missions were offset by its performance in other areas not requiring expenditure.

The two-stage concept (concept 5) was economically comparable to other concepts, but was found to be excessive in length. Because of its two-stage operation for high-energy missions, overall operations were found to be complex.

Based on the data obtained in this study, it is recommended that concepts 1 and 11 continue to be pursued in future studies.

Three intelligence module approaches were considered: totally modularized, partially modularized, and integrated. Total modularization allowed use of the IM separate from the propulsion module. In this application, it is necessary for a small module containing LO_2/LH_2 to provide adequate expendables for practical use. Such a configuration, along with the crew module, may be used for low earth orbit mini-station missions. It should be noted that the small propulsion module of concept 11 has about the right capacity for this type of mission. Therefore, integration of the IM components into the small concept 11 propulsion module would still allow the mini-station type missions.

The weight decreases resulting from partial or total integration of the IM into the propulsion module result in significant gross weight reductions, particularly for concept 1 [total integration reduces gross weight by 3600 pounds (1,600 kg) and partial integration reduces gross weight by 1800 pounds (800 kg)]. Integration of electronic functions into a module (partially integrated IM) allows all of the fluid functions to be located in the stage and results in only electrical interfaces between the IM and PM. From manufacturing, checkout, and refurbishment viewpoints, a partially integrated IM appears attractive.

At this point in the space tug program, a specific IM recommendation does not appear prudent. The choice is highly dependent upon propulsion module concept, on the payload capability of the shuttle, and upon the desirability of utilizing the IM for mini-station type missions.

In comparing the vertical-cylinder and horizontal-cylinder crew modules, it was found that both had similar functional characteristics when constrained by the EOS bay diameter. They also provided adequate volume for the 4-man 28-day lunar surface mission. The vertical-cylinder crew module is recommended on the basis of ease of integration of this concept with other vertical cylindrical modules. By modifying internal arrangements, this same module can be used for low earth orbit support missions and can provide rescue capability for up to 12 men.

STUDY LIMITATIONS

Because this was a pre-phase A study, the major study emphasis was placed on the Mission and Operations study task to provide insight into space tug operational characteristics and mission and system requirements. Approximately 60 percent of the total study effort was focused on this task. The remainder of the effort was expended on conceptual design, subsystems analysis, and planning documentation. For this reason, no detailed design effort was accomplished. The approach to the study was parametric, and as such, the results are beneficial even though mission characteristics and system characteristics (particularly the earth orbital shuttle) may vary in the future.

IMPLICATIONS FOR RESEARCH

The baseline space tug system was constrained to maximize the use of earth orbital shuttle and space station technology. In the areas of cryogenic insulation, zero-g propellant behavior, avionics, and possibly engine technology, shuttle technology appears to offer the major technology required by the space tug. Assuming that the shuttle orbital maneuvering system employs a new high chamber-pressure engine, the space tug main engines may closely match their specification. If the space tug has two to four engines, the thrust levels may match adequately. Close coordination of the tug and OMS engine development may lead to compatibility. Potential areas of difference include turbomachinery cycles and nozzle area ratio. For lunar missions, a throttling capability will be required.

A brief analysis of advanced avionics (advanced beyond shuttle and space station) indicated that potentially large inert weight savings may be realized by utilizing the improvements in the state of the art of sensors, guidance and navigation equipment, and computer equipment. These inert weight savings in turn lead to dramatic reductions in tug gross weight and cost. Additional studies to improve knowledge of the capabilities, mass properties, cost, and availability of these advanced components would be beneficial to allow key decisions in the space tug program.

SUGGESTED ADDITIONAL EFFORT

As a result of this study, several areas have been identified where additional effort would be beneficial. The most significant of these areas fall into the general categories of economic studies and operations and design studies.

Economic studies of payload retrieval, variations in tug design payload capability, and EOS orbital maneuvering system propellant utilization appear to be key elements of tug program economics. As shown, payload retrieval decreases the geosynchronous program cost by a large percent. Decreases in the space tug payload delivery capability at geosynchronous conditions from 10,000 pounds to lower values can have a significant effect on the ability to inject multiple payloads as well as to retrieve payloads. Use of EOS orbital maneuvering propellants significantly reduces propellant resupply cost for space-based operation or, alternately, decreases the required EOS payload capability for ground-based operations.

Future design studies should be closely tied to the EOS studies to assure compatibility in the key interface areas, including the space tug integration into the bay, removal on orbit, and retrieval. Because of the significance of orbital maneuvering system propellant sharing, considerable design attention is required to assure tug/EOS compatibility. More detailed tug design studies are required to develop design data, not only in the shuttle interface areas, but also in the design of space tug systems. The influence of advanced avionics on tug performance and costs should be more critically investigated. Additionally, the influence of varying degrees of tug autonomy on support from other systems (shuttle, space station, ground tracking, etc.) should be studied to determine the feasibility of utilizing other than a fully autonomous system.